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**(NASA-TN-79091) EVALUATION OF A BRAYTON
CYCLE RECUPERATOR AFTER 21,000 HOURS OF
GROUND TESTING (NASA) 28 p HC A03/NP A01**

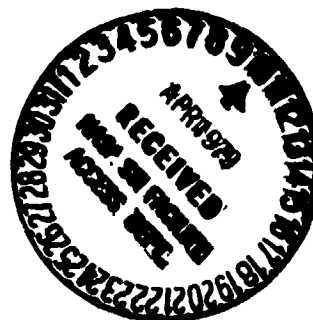
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**EVALUATION OF A BRAYTON CYCLE RECUPERATOR
AFTER 21,000 HOURS OF GROUND TESTING**

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SUMMARY

After ground testing a Brayton cycle system for 21 000 hours, the type 347 stainless steel, Ni-base brazed recuperator and associated ducting were removed for metallographic examination. Also examined were a stainless-steel/Hastelloy X bellows and an elbow of Hastelloy X ducting which was exposed to 11 000 hours of service. The examination indicated that manufacture of the recuperator including fitup and brazing of the counterflow, plate-fin core was well done. The recuperator operated satisfactorily in that 21 000 hours of ground testing were accomplished. However, loss of the krypton working fluid and subsequent air contamination of the system occurred due to braze cracks at the peripheral plate-bar joints in the recuperator. Attempts to repair these leaks were not completely successful. At the hot end of the recuperator, the 0.10-mm-thick fins were oxidized through the full thickness. Operation above the 675° C hot end design temperature was probably a contributing factor to fin oxidation. At midlength and at the cold (compressor) end, no fin oxidation was observed. The stainless-steel ducting, stainless-steel/Hastelloy X bellows, and Hastelloy X ducting operated satisfactorily, although some loss in ductility was observed in the Hastelloy X ducting.

INTRODUCTION

The NASA Lewis Research Center has been actively involved in the development of a closed Brayton cycle, power conversion system, for space applications (ref. 1). Ground testing has been conducted to give assurance that the Brayton system will operate satisfactorily in space. No apparent wear or failure mode that would prevent attainment of the 5-year life objective was found during inspection of two Brayton rotating (i.e., turbine-alternator-compressor) units after 21 000 hr of operation (ref. 1). The recuperator, however, experienced leakage problems during the long-term test, with significant loss of the primary working fluid, krypton.

An evaluation of the recuperator from the Brayton (unit 2, "B") engine was undertaken to assess overall structural integrity after the 21 000-hour exposure. The primary purpose was to evaluate the condition of the type 347 stainless-steel plate-and-fin core material, including the Ni-base brazed joints. Metallographic examination was also conducted on the associated type 347 ducting. A type 347/Hastelloy X bellows and Hastelloy X ducting on the hot (turbine) end of the recuperator, which saw 11 000 hours of service, were also examined. In the ducting and bellows investigations, primary emphasis was placed on determining the quality of the weld joints. The results of the examination of the recuperator and ducting are documented in this report.

RECUPERATOR FABRICATION AND OPERATION

In the intended application, the Brayton Engine is designed to operate continuously with a closed loop of He-Xe working fluid in the vacuum of space for 5 years. The

ground test discussed herein was conducted in air using krypton working fluid for reasons of economy. A schematic of the Brayton power conversion system is shown in figure 1. Energy for the ground test was supplied to the loop by means of an electric heat source (ref. 2). The turbine inlet temperature was 870°C , and the turbine scroll discharge temperature was 760°C (ref. 1). Design conditions for the recuperator (taken from ref. 3) are shown in table 1. A silicone liquid (Dow Corning 200) was used as the liquid coolant in the waste heat exchanger. The design conditions specify an inlet temperature at the hot (turbine) end of the recuperator of 675°C . On the cold (compressor) end an inlet temperature of 140°C was specified. Dimensions of the counterflow section (fig. 2) are also shown in table 1. Note that, in this design, the hot-gas fins are higher than the cold-gas fins, 3.9 mm versus 3.2 mm.

Type 347 stainless steel was used in the construction of the plate-and-fin design recuperator core and associated ducting. Brazing of the core was accomplished with AWS B-Ni-3 (Ni-3.1B-4.5Si) filler metal. Gas tungsten arc welding (GTAW) was used to fabricate the type 347 ducting and the Hastelloy X ducting between the recuperator and the turbine. A double wall, type 347/Hastelloy X bellows transition piece was fabricated using a combination of resistance seam welding and gas tungsten arc welding processes. The bellows assembly was subsequently joined to the type 347 and Hastelloy X ducting using the GTAW process.

The duration of the Brayton system ground test was 21 000 hours. However, because of a switch of the recuperator to another test rig during one of the shutdowns, the hot zone Hastelloy X ducting and the stainless-steel/Hastelloy X bellows saw only 11 000 hours of service. The recuperator experienced 16 thermal cycles from shutdowns of sufficient duration to permit engine cooling to room temperature. These shutdowns were caused by gas leaks in the recuperator, and in some cases by instrumentation or equipment failure (ref. 1). A recuperator leakage path for the krypton working fluid was detected early in the ground test at the plate-bar braze joints. These plate-bar braze joints in the peripheral areas of the recuperator were found to be areas of high thermal stress due to constraint and differences in material thickness (approximately a 10/1 ratio). The repair procedure involved the use of gas tungsten arc welding to seal the cracks.

Air entered the Brayton system because of the leaks in the recuperator and because the working fluid pressure sometimes approached atmospheric pressure, particularly when a leak became large.

Upon removal from the Brayton engine after 21 000 hours of operation, an additional leak source was discovered. A crack (disclosed by a helium leak test) had developed in the Hastelloy X turbine scroll along a weld (ref. 1).

RECUPERATOR EVALUATION

Recuperator Core

Two views of the recuperator assembly before sectioning are shown in figure 3. The recuperator was first saw cut through the core along the white lines. Next,

metallographic specimens were obtained from the inlet and outlet stainless-steel ducting and from the core (fig. 3(b)) using electrodischarge machining (EDM) procedures. The appearance of the core segments after removal of nine plugs by EDM is shown in figure 4.

With EDM no mechanical deformation is produced. This is important because of the thinness of the fins (0.10 mm), the relative brittleness of the braze metal, and the brittleness (as a result of oxidation) in some portions of the core. There was, however, an undesirable effect of EDM on the fins. This effect was localized melting. Apparently, the thin fins, particularly in oxidized regions, experienced sufficient heat buildup to produce the localized melting. Because of this, the surfaces to be examined metallographically were sectioned using an automated abrasive cutoff wheel at a very slow feed rate. Metallographic specimens were taken at both the center and at one end of the plugs as shown in figure 5. The offset rectangular fin-and-plate construction shown in figure 5(a) illustrates that good fitup was achieved at the braze joints. Good fitup is also evident in the plate-bar construction at the outer surfaces (fig. 5(b)).

At the hot end (plug 2A in fig. 3(b)), the entire wall of the fin was oxidized, as shown in figure 6. No oxidation occurred in the plate because of the protective coating provided by the brazing filler metal. The oxidation, although similar in pattern, was more extensive in the 3.2-mm-high fins (which carry the compressor discharge gas) than in the 3.9-mm fins (which carry the turbine exhaust gas). Material scraped from the oxidized fins was magnetic. X-ray diffraction of the oxidized fins revealed that the oxidation product was primarily Fe_3O_4 . The microstructures of plugs 2B and 2C were similar to that of plug 2A, which was described above. Thus, at the hot end of the recuperator, oxidation of the fins was severe.

At midsection of the counterflow core (plugs 4A, 4B, 4C in fig. 3(b)), no oxidation problem was observed, and the braze joints were of fair to good quality. In the typical plate-and-fin brazement microstructures (fig. 7) some voids and porosity are evident in the braze metal.

At the cold end of the recuperator, the brazed joints were of good quality with no evidence of deterioration. The microstructure shown in figure 8 for plug 6B also is typical for the other cold end locations (plugs 6A and 6C, fig. 3(b)).

Typical hot end braze cracks at a plate-bar joint (fig. 5(b)) are shown in figure 9(a). A gas tungsten arc repair weld of an earlier crack of this type is shown in figure 9(b). Although the weld repair technique appears to be successful in this case, it did not prove to be a viable solution to the leakage problem in the recuperator. A further attempt to alleviate this leak problem at the plate-bar braze joints involved gas tungsten arc welding a 1.5-mm-thick stainless-steel cover sheet over the sides of the recuperator as shown in figure 3(a). This permitted continuation of the long-term systems test with minimum interruption.

Stainless Steel Ducting

Sections were taken from the type 347 stainless-steel ducting at the hot end of the recuperator at the locations shown in figures 3(b) and 10 using electrodischarge machining (EDM) techniques. Sections 1A-1 and 1A-2 from the inlet ducting were examined and were found to be sound. However, the microstructure of section 1A-2 (fig. 11(a)) shows a minor scallop oxidation pattern at the inside surface of the weld. Section 1B at the outlet ducting was also free of flaws except for one slightly oxidized area at the inside surface (fig. 11(b)). Additional sections were taken further downstream in the outlet ducting (see figs. 3 and 12). Although the welds and base metal were sound (sections 1F, 1G, and 1H), localized minor oxidation was observed on the inside surfaces of the welds and base metal (fig. 13). In all of these areas in the ducting the oxidation is considered of minor significance because the affected area is a small percentage of the wall thickness.

Bend test specimens were taken from the location shown in figure 12. Duplicate specimens 2.04 by 16 by 57 mm were successfully bent about 60° at room temperature in a guided bend test over a 2t radius with the inside surface of the ducting loaded in tension. These specimens were then further bent to 180° in a vise. There was no evidence of cracking. These results show that the inherent good ductility of the type 347 stainless steel ducting at the hot end of the recuperator was retained.

At the cold end of the recuperator (figs. 3 and 14) the weld in the type 347 stainless steel ducting was sound. There was no evidence of oxidation at the inside surfaces in this area (fig. 15).

Bend test specimens were obtained near the location from which the metallographic specimen was taken (fig. 14). Duplicate specimens, 1.27 by 14 by 54 mm with the inner ducting surface in tension, passed a 60° guided bend test over a 2t radius at room temperature. The specimens were then bent 180° in a vise with no evidence of cracking, thereby demonstrating that the inherent good ductility was retained.

Hastelloy X Ducting

A portion of the Hastelloy X ducting, which carried the working fluid from the turbine exhaust to the recuperator is shown in figure 16. The double-wall bellows was made of type 347 stainless steel. During dismantling of the recuperator, the Hastelloy X material exhibited brittleness in that it cracked at the base of a knob at a fillet weld and separated from the ducting. By using EDM, section 1C in figure 17 was obtained without breaking off the small part of the knob that remained attached to the ducting. Figure 18(a) illustrates the incipient toe crack in the ducting immediately adjacent to the fillet weld. The typical base-metal microstructure is shown at higher magnification in figure 18(b).

The gas tungsten arc girth weld between the knob and the flange (section 1C-2 in figure 17) was sound as shown in figure 19(a). Edge-flange weld 1C-3 was also sound (fig. 19(b)). The other gas tungsten arc welds 1C4, 1E, and 1X (fig. 17) were also free of flaws.

Bend specimens were obtained from the ducting near the location of the knob (fig. 17). Two specimens 1.24 by 16 by 55 mm were tested at room temperature with the inside surface of the ducting in tension. The first specimen survived a guided bend test of 45° over a 4t bend radius. Subsequent free bending of the first specimen in a vise resulted in failure at 120° of bending. The second specimen survived a 2t radius guided bend of 60° but failed at 110° in the free bend. Two as-received Hastelloy X sheet reference specimens, 1.35 by 15 by 55 mm, were bent in a similar manner. A full, 180° free bend was achieved for both specimens. This shows the inherent excellent ductility of Hastelloy X material in the as-received condition and demonstrated there was a ductility loss due to the ground testing exposure.

Stainless/Hastelloy X Bellows

The type 347 stainless steel bellows (shown in figs. 16 and 20) was welded to the type 347 stainless-steel hot end inlet ducting shown in figure 3. A section was removed by EDM from the Hastelloy X end of the bellows assembly at the location shown in figure 20. The welding details of this section are shown in the photomicrograph in figure 21. In fabrication of the double wall bellows, the ends of the stainless-steel bellows were sandwiched between Hastelloy X rings. Resistance seam welding was used to fusion weld these members together. A gas tungsten arc fillet weld was subsequently used to join the ends of double wall bellows and the two Hastelloy X rings. Thus, these members were welded at two locations using two different welding processes. Both the resistance and arc welds are sound. The weld shown on the right in figure 21 is a gas tungsten arc butt joint between the Hastelloy X bellows assembly member and the Hastelloy X ducting.

DISCUSSION

The performance of the recuperator in the systems test was generally satisfactorily in that 21 000 hours of ground testing was achieved. Leakage of the primary working fluid, however, occurred at cracked plate-bar braze joints. High thermal stress due to constraint and differences in material thickness produced these cracks.

Fabrication techniques used in the construction of this complex heat exchanger were quite good as indicated by the quality of the fit-up and brazing of the plate-fin structure. Recuperator ducting materials were in good condition after the ground test, even though some loss in ductility was noted in the Hastelloy X parts. The severe oxidation of the type 347 fins appeared unusual. Even though leakage to the atmosphere occurred several times as a result of the cracking problem, the extent of oxidation of the fins appeared severe for an operating temperature of 675°C . A cursory study of fin oxidation versus temperature was undertaken. Segments of the recuperator core for these experiments were obtained from the compressor inlet or cold end which had shown no evidence of oxidation in service. Heat treatments were conducted on these core segments in stagnant air for 100 hours at

675° C, 800° C, and 1000° C. The results are shown metallographically in figure 22. At 675° C, oxidation of the stainless steel does not appear to be a problem. At 800° C, surface oxidation is evident. In addition, at one location oxidation has proceeded half-way through the wall of the fin. Thus, if a temperature exposure occurs in the vicinity of 800° C for 100 hours in a stagnant air environment, severe oxidation of type 347 stainless steel can be anticipated. Exposure to 1000° C for 100 hours completely destroys the thin-wall fins. These results suggest that the recuperator may have experienced higher temperatures than 675° C.

Redesign and fabrication of an improved recuperator for the Brayton system was undertaken shortly after the leakage problems were noted. The final recuperator design (ref. 4) incorporates a new manifold construction and header bar shapes to alleviate thermal stress. Double contaminant side plates were used in order to further insure against leaks to the atmosphere. Hastelloy X is specified as the recuperator material because of its superior strength and fabricability compared with type 347 stainless steel. Gold-base brazing filler metal is used throughout the recuperator. Test results (ref. 4) show that this final design recuperator was operated successfully. It withstood 100 startup and shutdown cycles (inlet temperature, 722° C) without developing a fatigue crack that would result in external leakage. Heat transfer performance with He-Xe working fluid slightly exceeds the requirements.

SUMMARY OF RESULTS

A type 347 stainless-steel Brayton cycle recuperator and integral stainless-steel ducting was inspected after 21 000 hours of ground testing. The recuperator operated at a nominal temperature of 675° C at the hot (turbine) end. Hastelloy X elbow ducting and a stainless-steel/Hastelloy X bellows which saw 11 000 hours of testing were also inspected.

1. Workmanship in the recuperator brazement consisting of plate-and-fin core and the plate-bar sides was very good. Braze cracks, however, occurred at the plate-bar joints apparently because of thermal stresses.

2. Leaks in the Brayton system resulted in air contamination and through-the-wall oxidation of the 0.10-mm wall stainless-steel fins at the hot end of the recuperator. Temperature excursions above the 675° C design temperature may have occurred at the hot (turbine) end to produce oxidation of the thin-wall fins.

3. The stainless-steel ducting was still serviceable after the ground test in that the excellent base metal ductility was retained. All gas tungsten arc weld joints were sound.

4. No oxidation or other detrimental effects were observed in the ground tested stainless-steel/Hastelloy X bellows.

5. A loss of ductility was observed in the Hastelloy X ducting during the ground test, but service performance was not affected. Gas tungsten arc welds in the Hastelloy X ducting were of high quality.

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1. Dunn, James H.: Inspection of Two Brayton Rotating Units after Extensive Endurance Testing. NASA TM X-73569, 1976.
2. Macosko, Robert P.; et al.: A Compact 90-Kilowatt Electric Heat Source for Heating Inert Gasses to 1700° F. NASA TM X-52778, 1970.
3. Morse, C. J.; Richard, C. E.; and Duncan, J. D.: Brayton Heat Exchanger Unit Development Program, Final Report. (AIRESEARCH-71-7450, AiResearch Mfg. Co.; NASA Contract NAS3-10607.) NASA CR-120816, 1971.
4. Killackey, J. J.; Graves, R.; and Mosinskis, G.: Design and Fabrication of the Mini-Brayton Recuperator (MBR). (AIRESEARCH-78-14972, AiResearch Mfg. Co., NASA Contract NAS3-18029.) NASA CR-159429, 1978.

TABLE 1. - RECUPERATOR OPERATING CONDITIONS AND DESIGN^a

Working fluid (gas):

Design ^bHe-Xe mixture
 For ground tests Krypton

Liquid coolant:

Type Dow Corning 200
 Viscosity at 25° C, cS 2

Hot gas:

Gas flow rate, kg/sec 0.582
 Inlet temperature, °C 675
 Inlet pressure, ^c kPa (absolute) 166

Cold gas:

Gas flow rate, kg/sec 0.576
 Inlet temperature, °C 140
 Inlet pressure, ^c kPa (absolute) 297

Counterflow section:

Flow length, mm 500
 Flow width, mm 215

Hot-gas fins:

Height, mm 3.9
 Fins per 2.54 cm (per inch) 16
 Thickness, mm 0.10
 Type Offset rectangular

Cold-gas fins:

Height, mm 3.2
 Fins per 2.54 cm 16
 Thickness, mm 0.10
 Type Offset rectangular

Nominal plate thickness, mm 0.20

Number of sandwiches, each side 66

Stack height, mm 503

Side plate thickness, mm 1.52

^aRef. 3.

^bMolecular weight, 83.8.

^cStructurally, the recuperator hot side is designed to withstand
 210 kPa (absolute) and the cold side 386 kPa (absolute).

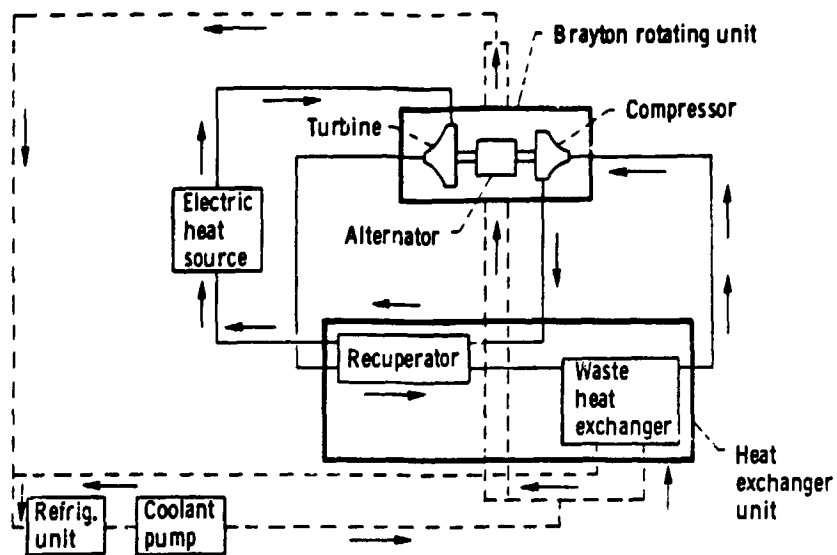


Figure 1. - Schematic of Brayton power conversion system.

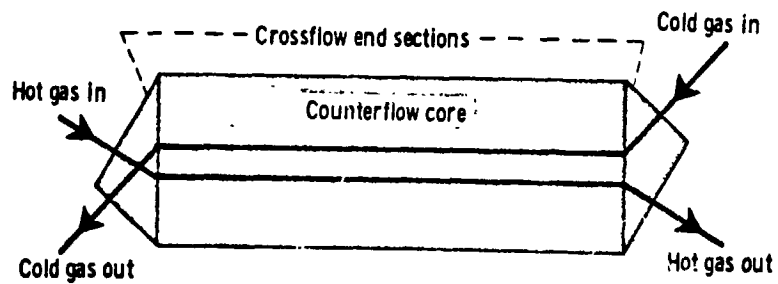
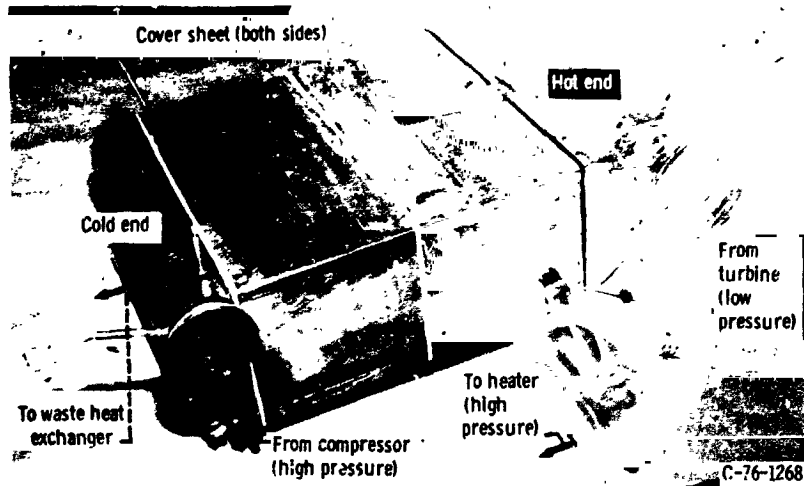
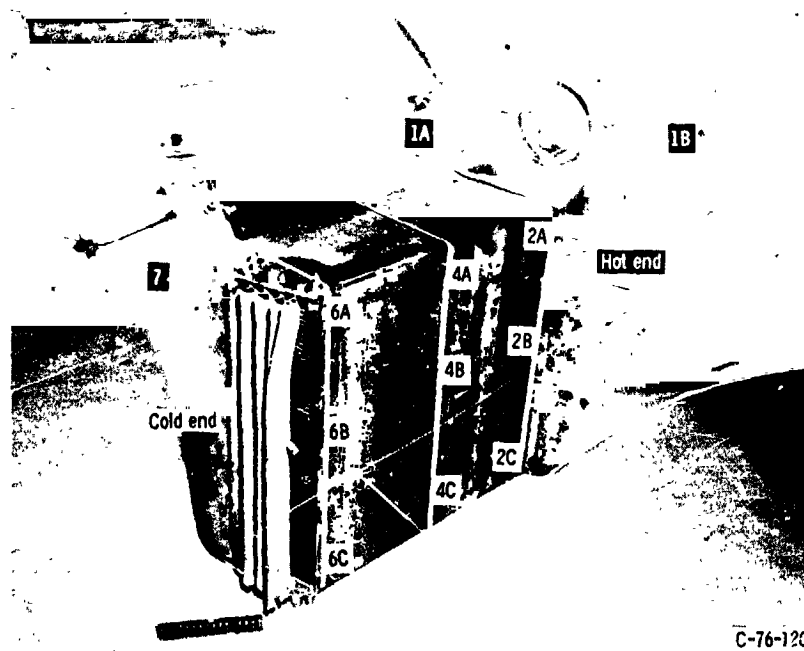


Figure 2. - Recuperator schematic.

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(a) Gas flow pattern, white lines indicate sectioning locations.



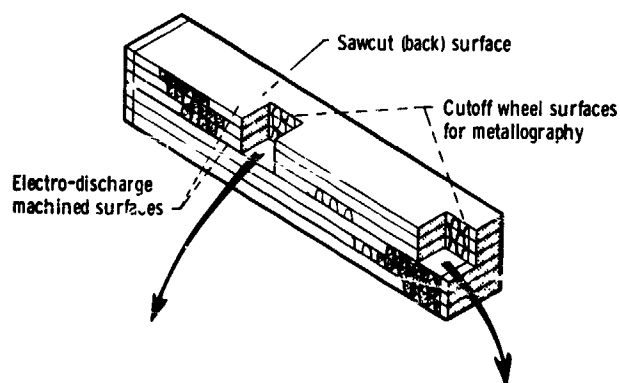
(b) Locations of plug removal from the core and sections taken through weld joints in the ducting.

Figure 3. - Type 347 stainless steel recuperator assembly.

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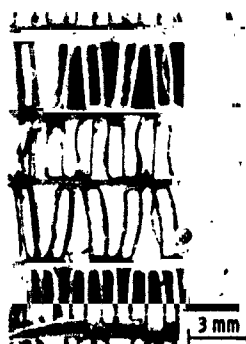


Figure 4. - section recuperator core with plugs removed.



Section 4B4

(a) Central portion of plug showing plate/fin construction.

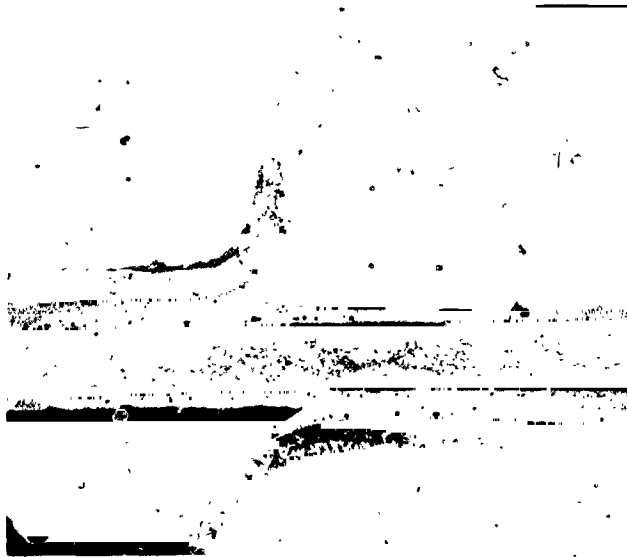


Section 6B7

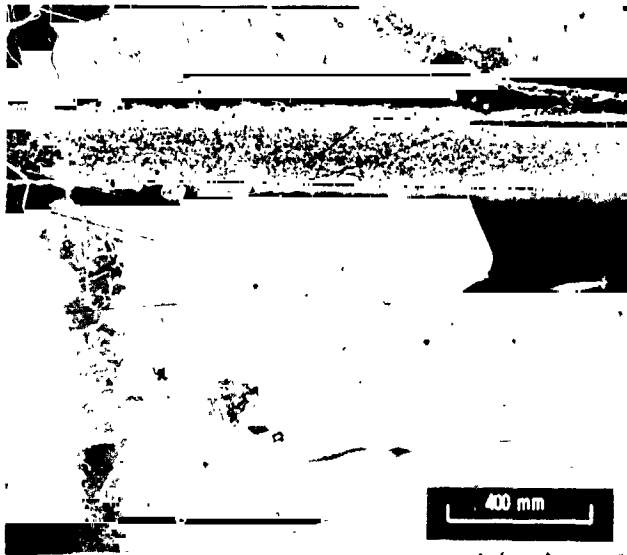
(b) End section of plug showing plate/bar construction at the outer surface.

Figure 5. - Brayed type 317 stainless steel recuperator core construction.

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(a) End section of plug 2A showing oxidation through a fin.



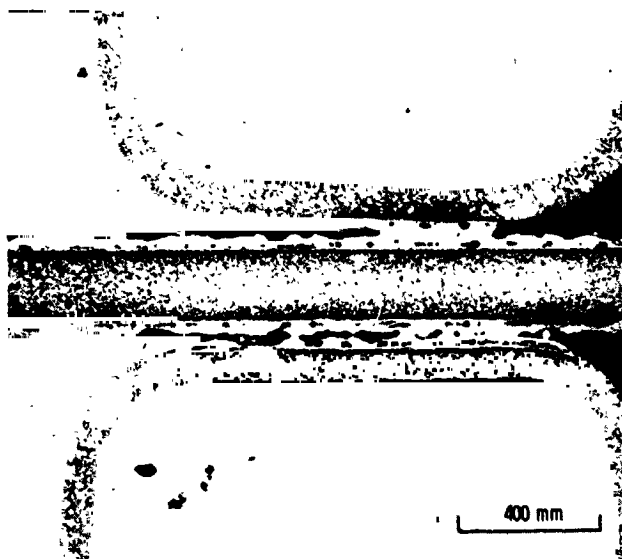
(b) Severe fin oxidation at center section of plug 2A.

Figure 6. - Typical oxidation of brazed type 347 stainless steel plate /fin recuperator near hot end.

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(a) End section of plug 4B braze.



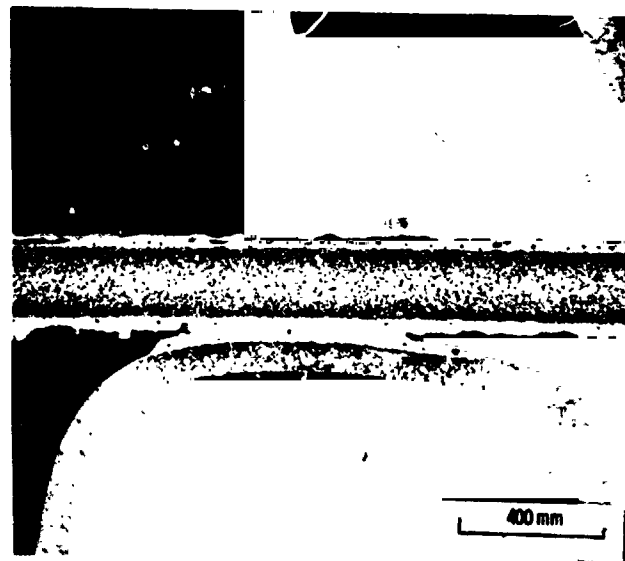
(b) Center section of plug 4B braze.

Figure 7. - Typical plate / fin type 347 stainless steel recuperator joints midway between hot and cold ends.

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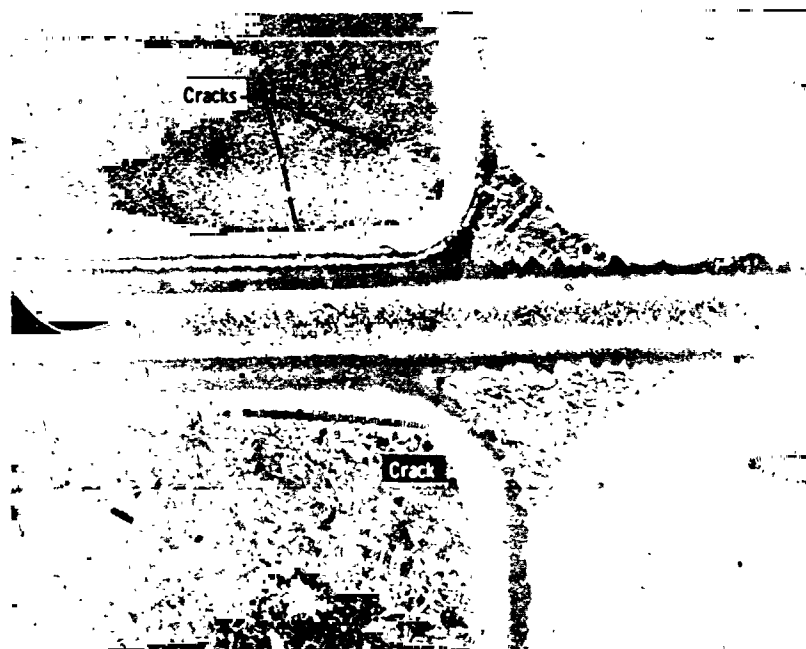
(a) End section of plug 6B braze.



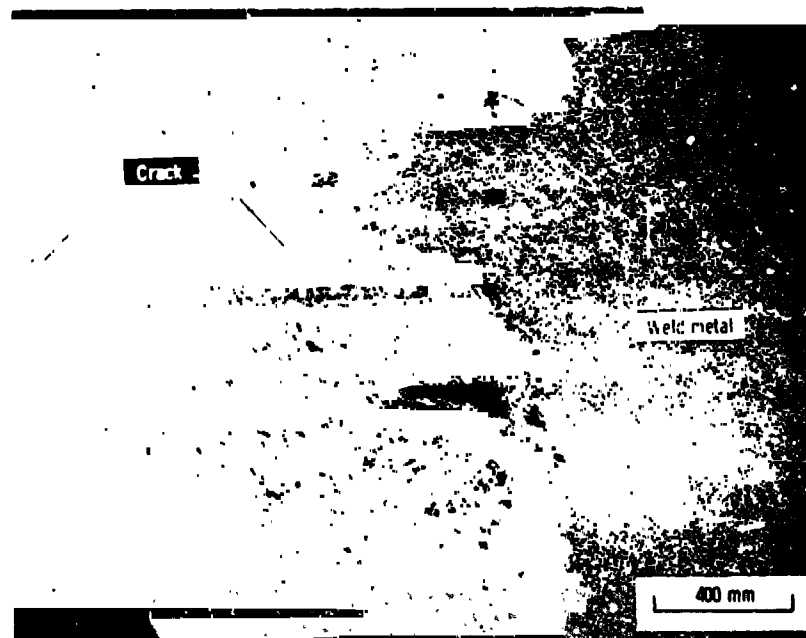
(b) Center section of plug 6B braze.

Figure 8. - Typical type 347 stainless steel fin recuperator at the cold end.

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(a) Braze cracks near braze-bar interface and in braze fillets, plug 6R



(b) Gas tungsten arc weld repair of braze crack, plug 2A.

Figure 9. - Braze cracking and weld repair areas in type 347 stainless steel plate /bar joints.

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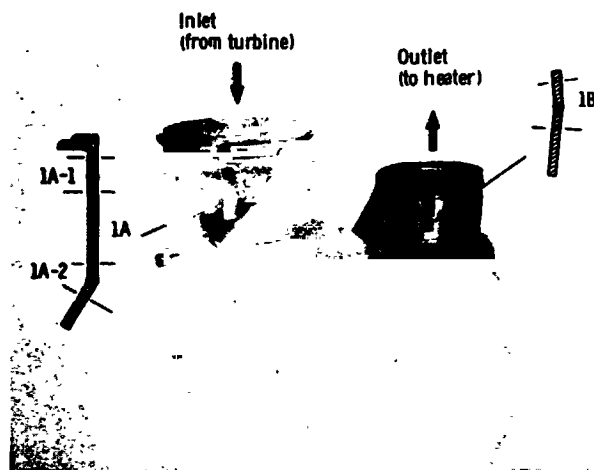
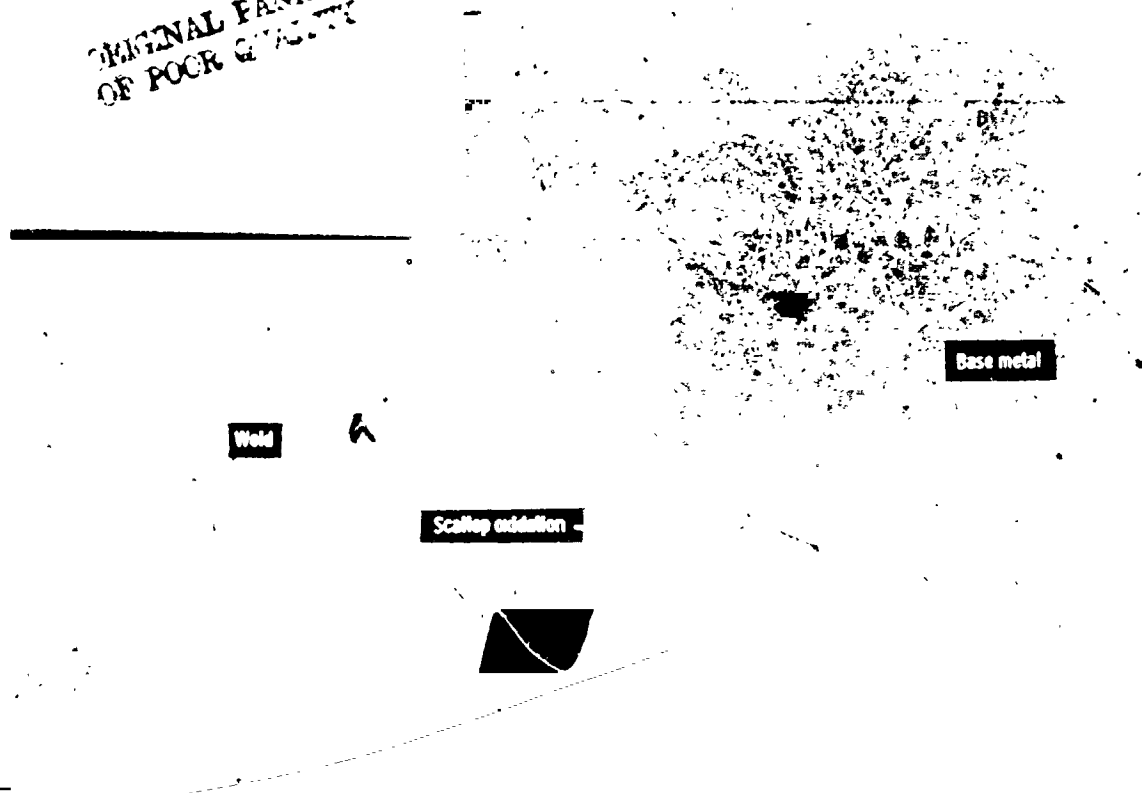


Figure 10. - Cutout locations in type 347 stainless steel ducting at the hot end of the recuperator.

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(a) Section 1A-2 showing minor weld oxidation, hot gas inlet from turbine.



(b) Section 1B $\frac{1}{2}$ heated gas outlet.

Figure 11. - Gas tungsten arc weld joints in type 347 stainless steel ducting at hot end of the recuperator.

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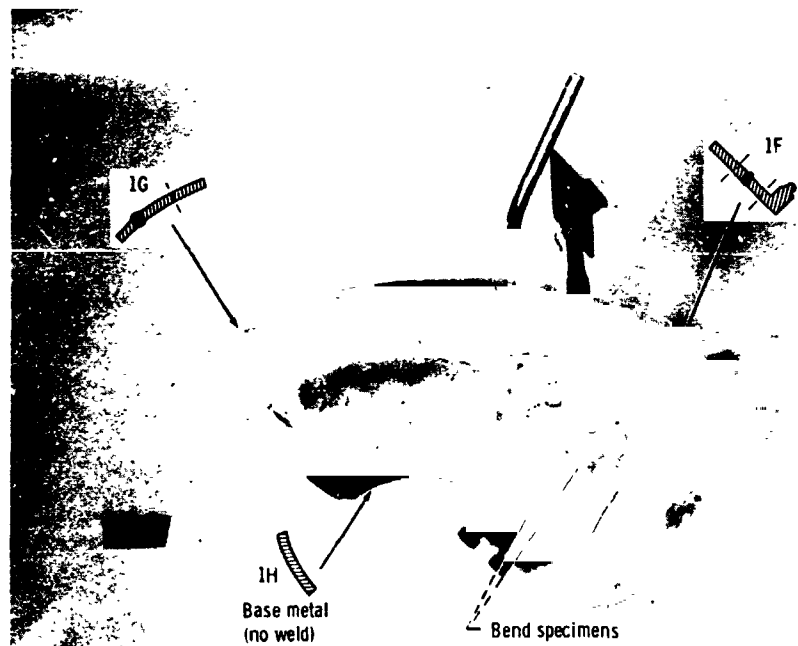
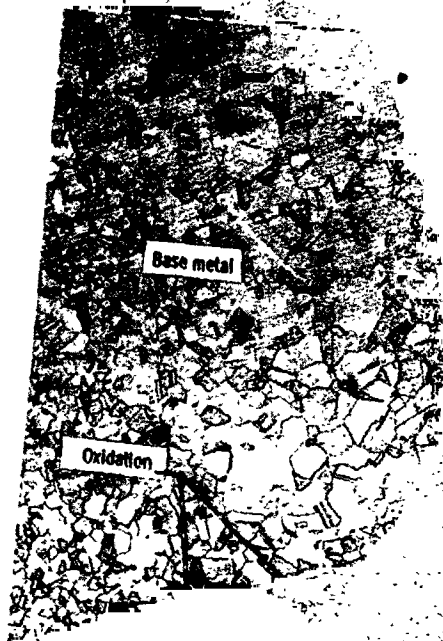
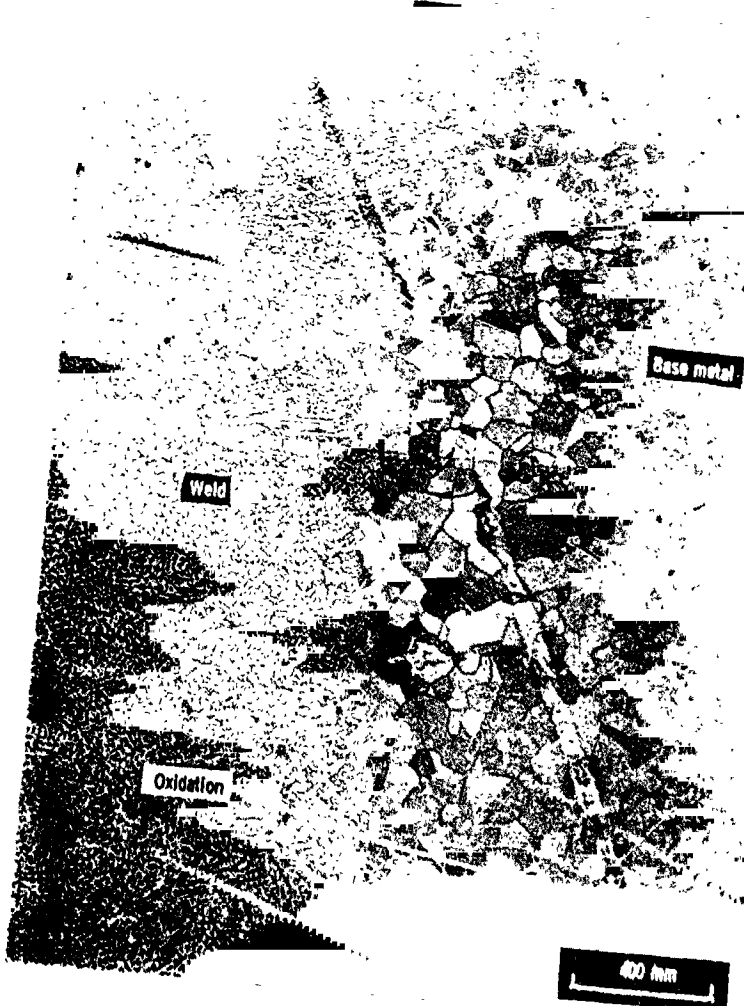


Figure 12. - Locations of cutouts and bend specimens in type 347 stainless steel outlet ducting at hot end of recuperator.

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(a) Thin oxidation layer at inside of
weld joint, section 1G.



(b) Slight oxidation at inside surface
of weld and in heat affected zone,
section 1F.

Figure 13. - Gas tungsten arc welds, type 347 stainless
steel at the hot end of the recuperator.

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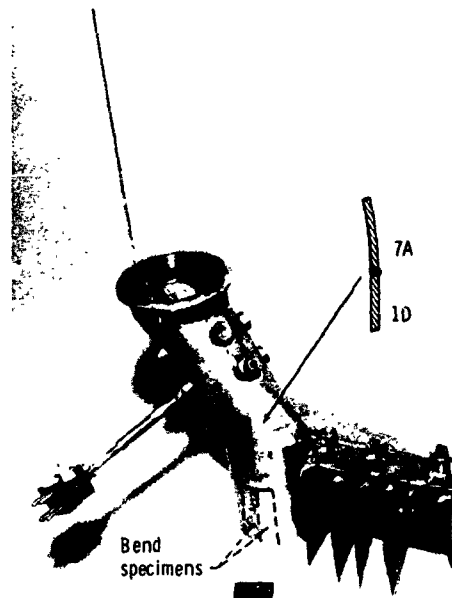


Figure 14. - Cutout and bond specimen locations in type 347 stainless steel ducting at cold end of the recuperator.

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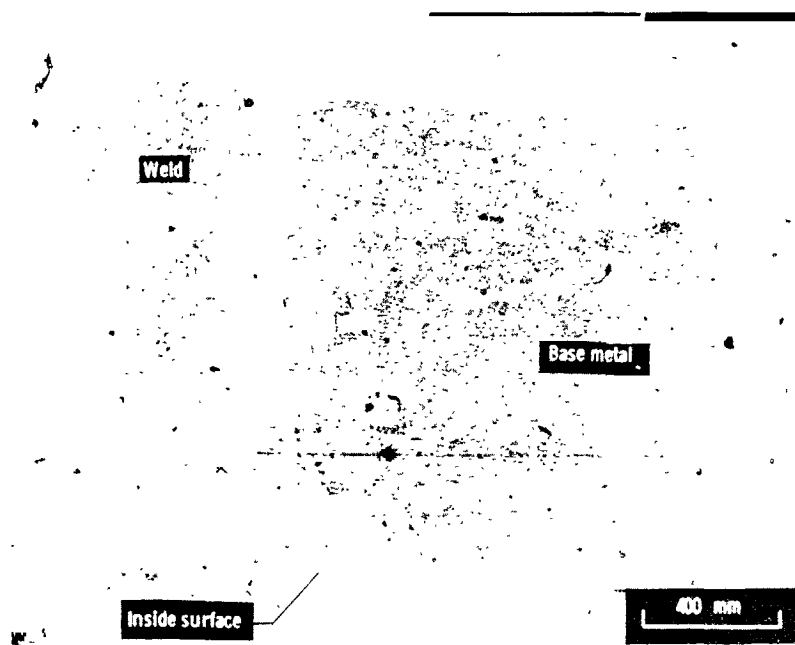


Figure 15. - Typical sound weld in type 347 stainless steel ducting at section 7a, cold end.



Figure 16. - hastelloy X elbow / type 347 stainless steel double-wall bellows assembly.

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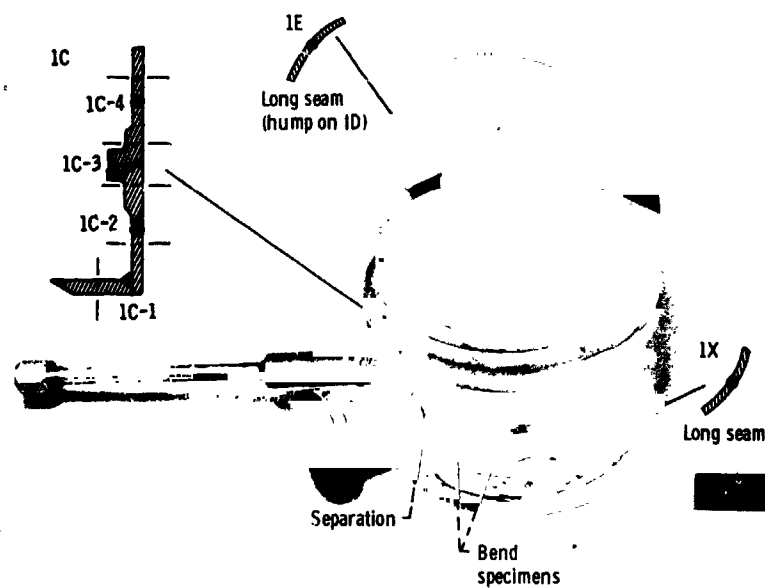
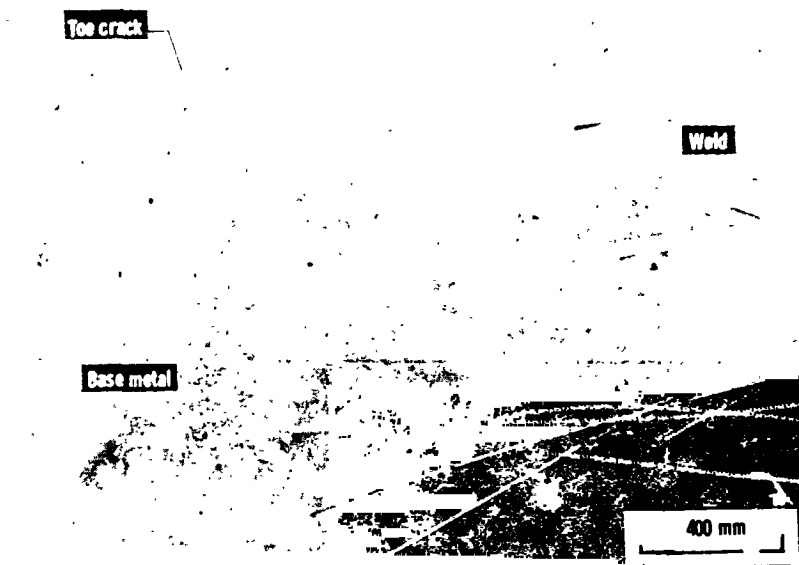
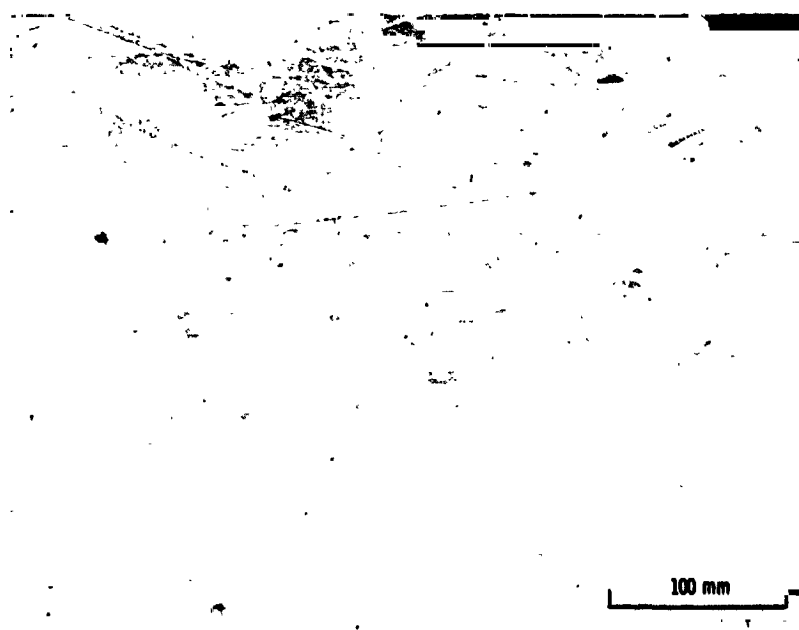


Figure 17. - Portion of Hastelloy X elbow closest to turbine exhaust showing locations of cutout sections and bend specimens.

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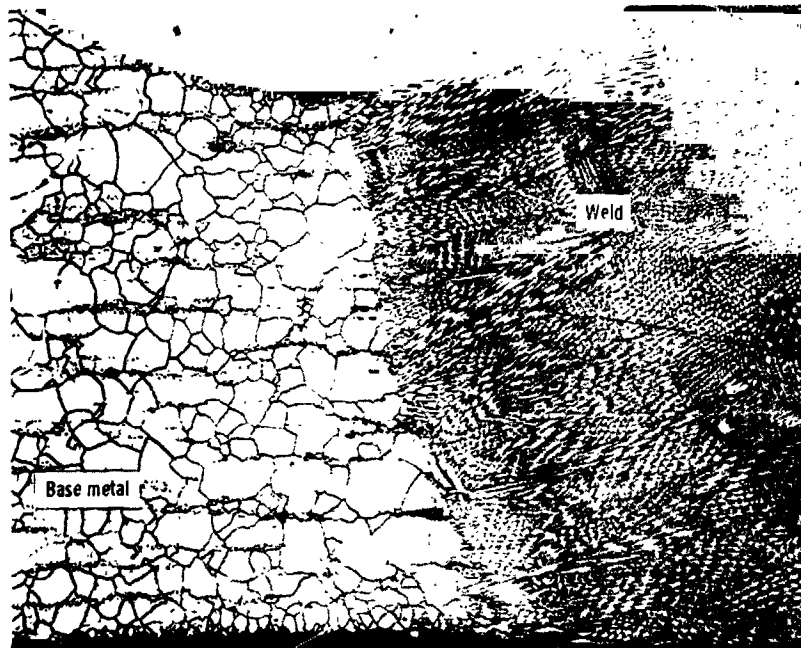
(a) Incipient toe crack in section 1C - 1 at outer surface.



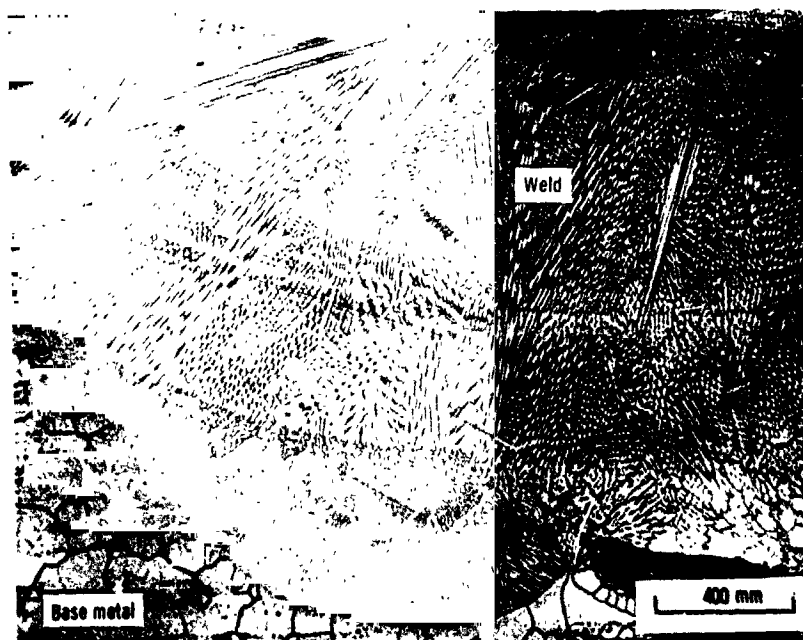
(b) Typical base metal microstructure from section 1C-2.

Figure 18. - Incipient crack near Hastelloy X gas tungsten arc fillet-weld and Hastelloy X base metal microstructure at higher magnification.

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(a) Flange side of butt joint 1C-2.



(b) Edge - flange weld 1C-3.

Figure 19. - Typical gas tungsten arc welds in Hasrelloy X ducting.

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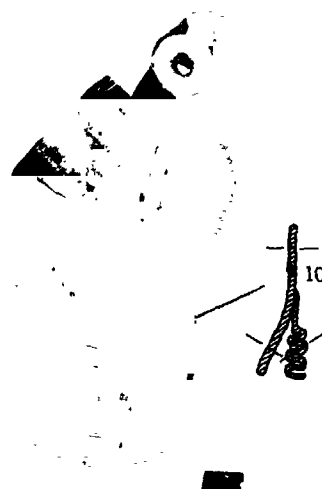


Figure 20. - Cutout location at junction of Hastelloy X elbow and type 347 stainless steel bellows.

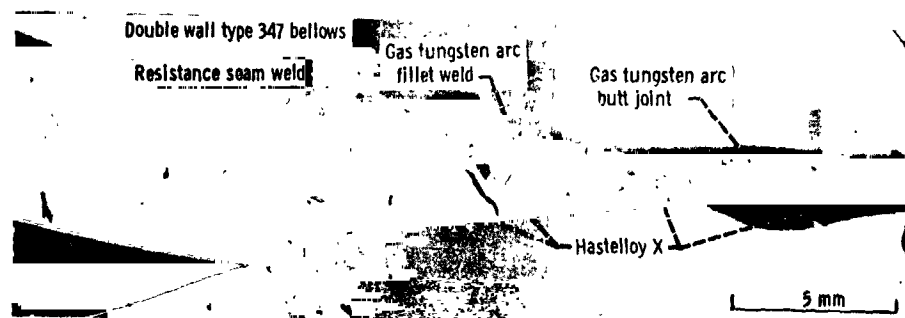
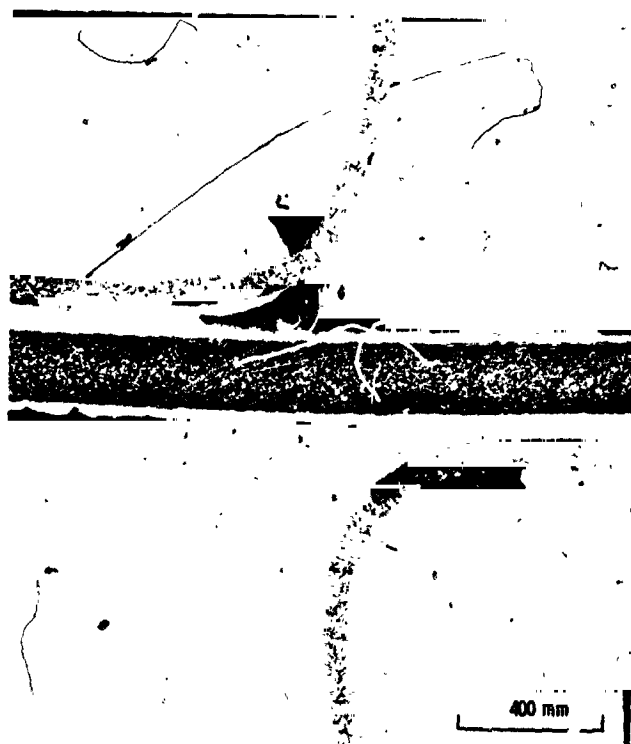
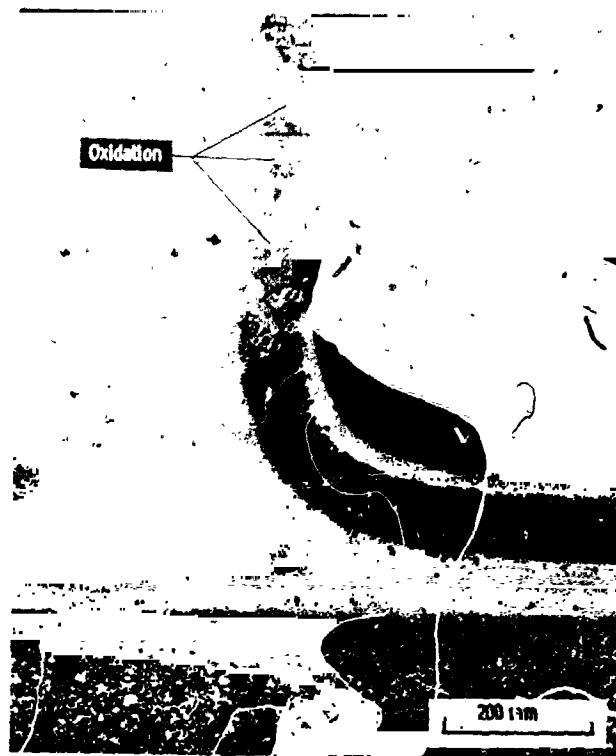


Figure 21. - Fabrication and welding details of the double-wall type 347 stainless steel bellows and Hastelloy X connecting parts.

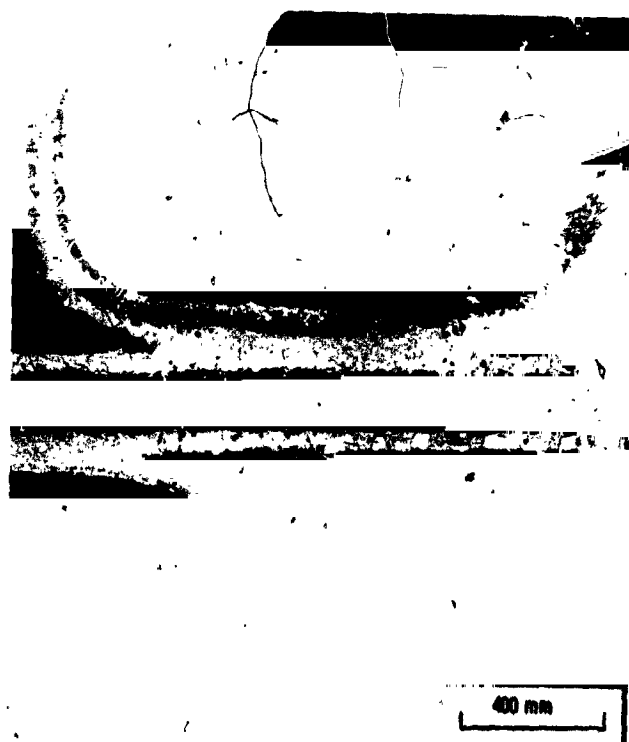
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(a) Oxidation free fins after 100 hours at 675 C.



(b) Surface and internal oxidation after 100 hours at 800 C.



(b-1) Complete oxidation of the fins after 100 hours at 1000 C.

Figure 22. - Oxidation effect on brezed type 347 stainless steel recuperator core due to 100 hours stagnant air exposure at 675 C, 800 C and 1000 C.